Satellite Altimetry

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Project Summary

The launch of the Jason-2/Ocea Surface Topography Mission (OSTM) on June 15, 2008, will mark the beginning of a major transition for NOAA. NOAA and it's partner operational agency, EUMETSAT, will begin assuming responsibility for continuing the record of global sea level rise established by NASA and CNES with the Topex and Jason-1 satellite altimeter missions. The NOAA Laboratory for Satellite Altimetry (LSA) will play an important role in this transition, helping insure that Jason-2 observations satisfy the stringent requirements of a climate data record and providing scientific leadership, both inside and outside of NOAA. This responsibility is expected to grow with the proposed FY10 start of a Jason-3 mission to be launched in 2013.

In order to best take advantage of these changing roles and responsibilities, we propose to substantially redirect the OCO Satellite Altimetry Program in FY08 and onward as follows:

- The design and maintenance of (1) the NOAA Radar Altimeter Database (Scharroo/Altimetrics) and (2) the Altimeter/Tide Gauge Calibration System (Mitchum/USF & Soreide/PMEL) will continue but with NOAA Jason-2 Program funds rather than OCO funds

- The routine computation of precise Geosat Follow-On orbits (Lemoine/NASA) will continue with OCO funds.

- The research on connecting the Geosat and Topex global mean sea level time series (Miller/LSA) will be completed with OCO funds in FY08.

- The reconstruction of past sea level change from altimeter and tide gauge observations (Nerem/UC) will be replaced with a new OCO supported activity, research into the discrepancy between observed and model predicted sea level rise (Miller/CICS).

Background

Sea level rise is widely recognized as possibly one of the most devastating consequences of global warming. Nearly all shoreline areas around the world will eventually be affected by rising levels, either from erosion or inundation. The impact on hundreds of millions of coastal inhabitants, especially those in underdeveloped countries, may be severe.

The most compelling evidence of sea level rise comes from satellite radar altimeter observations. Figure 1 shows the altimeter-determined trend over the past 14 years compared with two historical estimates based on tide gauge observations. During the late 1800's – early 1900's the global mean rate was about 1 mm/yr, while during the second half of the 20th century the rate increased to 1.8 mm/yr. The satellite altimeter observations indicate an even greater rate for the past decade, 3.1 mm/yr.

Measuring and explaining the cause of this apparent acceleration is a principle goal of the OCO Satellite Altimetry Program.

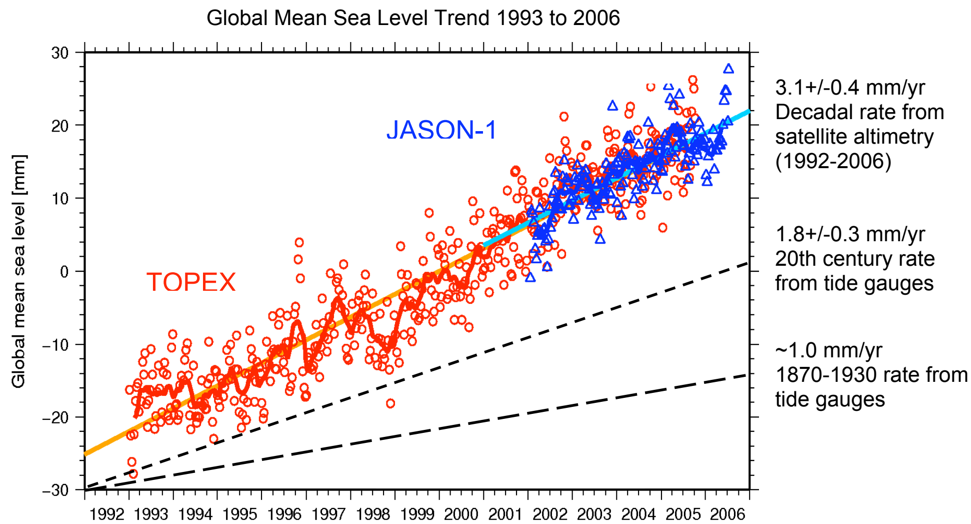

Figure 1. Global mean sea level trend from 1993 to 2006 based on TOPEX and JASON-1 altimeter observations. The trend over the past 14 years is roughly 2 times greater than the trend over the last half century and 3 times greater than the trend over the late 1800's – early 1900's. The latter two trends are based on tide gauge observations that only produce useful global estimates on intervals greater than 50 years, due to their limited geographical coverage.

To put the current observations into perspective, it is important to note that the altimeter measured rate of sea level rise is 50% greater than the "best-estimate" predicted by the IPCC Third Assessment Report (TAR) climate models (Rahmstorf et al., 2007) and the Four Assessment Report (FAR) predictions are probably not much better (Leuliette, 2006). The shaded area in Figure 2 represents the range of the TAR sea level predictions from 1990 onward. (The models are initialized with actual ocean and atmosphere observations prior to 1990, then allowed to run forward in coupled mode, without data assimilation, from 1990 onward). The model estimates diverge immediately from the observed sea level rise shown in the upper blue and red curves. Whereas the observed rate was 3.3 ± 0.4 mm/yr from 1993-2006, the best-estimate TAR projection is less than 2 mm/yr. The cause for this large discrepancy is unknown, and while it could represent short-term natural variability not captured by the models, failure to project even near-term sea level rise serves as a warning. The IPCC long-range projections presently being used to develop climate adaptation strategies could have similar problems.

Determining the cause of the observation/model-projection discrepancy is another principle goal of the OCO Satellite Altimetry Program.

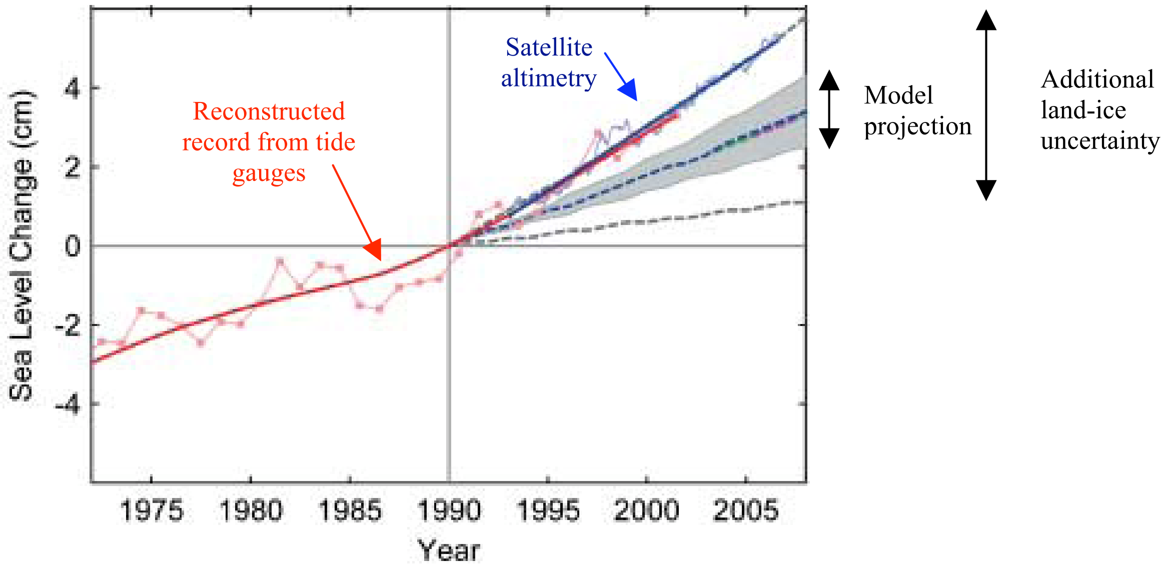

Figure 2. Sea-level data based primarily on tide gauges (annual, red) and from satellite altimeter (3-month data spacing, blue, up to mid-2006) and their trends. All trends are nonlinear trend lines and are computed with an embedding period of 11 years and a minimum roughness criterion at the end (*6*), except for the satellite altimeter where a linear trend was used because of the shortness of the series. Sea level, data are shown as deviations from the trend line value in 1990, the base year of the IPCC scenarios. (Figure extracted from Rahmstorf, S., A. Cazenave, J.A. Church, J.E. Hansen, R.F. Keeling, D.E. Parker, and R.C.J. Somerville, Science, 316, 709, 2007.)

Over the past several years we have developed several program elements that contribute toward these goals. They include:

- The design and maintenance of the NOAA Radar Altimeter Database System (RADS), a collection of all of the different satellite missions processed and inter-calibrated in a consistent manner, widely used by the research community.
- The production of high precision Geosat and Geosat-Follow-On (GFO) orbits.
- The reconstruction of past sea level change from a combination of satellite altimeter and tide gauge measurements.
- Research into new methods of calibrating altimeter observations with tide gauge measurements.
- The design and maintenance of a web-based, public source of altimeter/tide gauge calibration information for all current and past satellite missions.

Satellite altimetry is a unique type of ocean remote sensing observation because it provides much more than a surface measurement. Spatial and temporal variations in sea surface height are driven by temperature and salinity changes throughout the water column as well as changes in the total mass of the water column When combined with in-situ density observations, like those obtained from the Argo profiler array, satellite altimetry provides an ideal tool for monitoring changes in the Earth's heat budget and hydrologic cycle.

The NOAA Laboratory for Satellite Altimetry (LSA) has long been involved in climate related studies of sea level, having participated in every satellite altimeter mission: Geos-3, Seasat, Geosat, ERS-1, Topex/Poseidon (T/P), ERS-2, Geosat Follow-On (GFO), Jason-1, and

Envisat. Many of these have been research programs or operational demonstrations. However, since the mid-1990s it has been possible to produce quick-look, altimeter-generated analyses of sea surface height with sufficient accuracy and resolution to have operational utility. This capability is largely due to advanced satellite orbit determination techniques based on systems like the Global Positioning System. As a result, NOAA now incorporates satellite altimetry in a number of its operational products. For example, near-real time sea surface height analyses are assimilated into NCEP ocean models used to forecast El Niño, hurricane intensification, and coastal circulation. NOAA/LSA also maintains the Radar Altimeter Database System (RADS), used to analyze climate time scale phenomena, such as global sea level rise.

Because of the value of altimetry to NOAA and the U.S. Navy, a commitment has been made to fly altimeters operationally as part of the National Polar-Orbiting Operational Satellite System (NPOESS) beginning in 2013. In the meantime, NOAA must continue to leverage its resources to take advantage of existing satellite altimeter missions, and prepare to assume responsibility for the Jason-2 ground system beginning in 2008.

This project contributes to the NOAA goals (1) Understand climate variability, and (2) Serve society's needs for weather and water information. It provides the satellite altimeter "research-to-operations" component of NOAA's Program Plan for Building a Sustained Ocean Observing System for Climate.

LSA maintains connections with many agencies, institutions, and programs. LSA staff members serve on NASA's Ocean Surface Topography Science Team, the Envisat altimeter advisory group, and science teams for CryoSat, and IceSat. See http://ibis.grdl.noaa.gov/SAT/

FY07 Accomplishments

a.) Operational Support of the NOAA Radar Altimeter Database System (RADS): Altimetrics, LLC

In order to monitor global sea level rise and other ocean climate phenomenon with satellite altimetry, it is essential that records from different satellite missions be processed and inter-calibrated in a consistent manner. The NOAA Radar Altimeter Database System (RADS), designed and maintained by Remko Scharroo serves that purpose, as well as providing a tool for studying important ocean "weather" problems such as hurricane intensity forecasting. Over the past year, data from the three currently functioning altimeters (Jason-1, Envisat, GFO) was added to RADS. Many significant improvements were made to the Geosat data set (1985-1988), including the development and implementation of a new ionosphere correction model and the incorporation of new, more precise orbits computed separately on this grant (**Activity (b) GFO & Geosat Precise Orbit Determination).** The impact of all of these changes is evident in the improved Geosat global sea level trend estimate (**Activity (d) Altimeter/Tide Gauge Calibration Research).**

b.) GFO and Geosat Precise Orbit Determination.

The U.S. Navy's Geosat Follow-On (GFO) altimeter mission has been operational since 2000. During 2007, the LSA used OCO funds to support the computation of precise orbits (F. Lemoine, NASA/Goddard) and worked closely with the Navy, NASA, universities, and project contractors to prepare and distribute final, research-quality Geophysical Data Records (GDRs). Thus far, LSA has produced 6 years of GDRs and distributed the data to users on DVD http://ibis.grdl.noaa.gov/SAT/gfo/). GDR production and distribution will continue routinely for the life of the GFO mission. In addition to the research data sets, GFO is a source of near-real time sea surface height that is used by the Navy and NOAA for ocean and atmosphere operations. As an example, the National Hurricane Center uses all available altimetry to compute "hurricane heat potential" maps as an aid to forecasting storm intensification. GFO contributes significantly to this activity as evidenced by a recent *EOS* articles on Katrina, published by members of the LSA (Scharroo, R., W. H. F. Smith, and J. L. Lillibridge ,2005, 2006).

OCO funds were also used to pay for the computation of new, more precise orbits for the final 2 years of Geosat, the 17-day Exact Repeat Mission (November 1986 to December 1988). (The orbits for the first 1.5 years of Geosat, the no-repeating Geodetic Mission, were upgraded in fy07). The new ERM orbits were computed using an improved gravity field based on GRACE observations, greatly reducing the random errors from 14 to 7 cm rms, with some larger values late in the mission due to high solar activity. This work is part of an effort by the LSA to upgrade the quality of the Geosat data set (see **(a),** above and (**d**) below) and thus make it possible to determine more precisely the bias between the Geosat and TOPEX global mean sea level time series

c.) Predictions of Regional Sea Level Change Patterns by 2100; R.S. Nerem and S. Dorsi, Univ. of Colorado

The following reflects a change in the UC component of our FY07 Work Plan, previously aimed at reconstructing past sea level change from a combination of altimeter and tide data. The new project, "Predicting Regional Sea Level Change Patterns by 2100", fits more closely with our second principle objective: determining the cause of the observation/model-projection discrepancy.

Global mean sea level varies mainly in response to two factors: 1) the warming of the oceans, which causes thermal expansion or thermosteric sea level change, and 2) the exchange water between the continents and the oceans. The latter has been thought to cause sea level to rise uniformly around the globe, hence it has often been termed "eustatic" sea level rise. However, *Mitrovica et al.* [2001] showed that the regional patterns of sea level change associated with melting ice in Greenland, Antarctica, and mountain glaciers outside of the polar ice sheets are not uniform. In fact, sea level may change very little in some locations in the proximity of the melting ice. This is due to the gravitational attraction of the ice on the ocean water surrounding the ice. For example, sea level rise caused by melting ice in Greenland is almost entirely offset along the coast of Greenland as sea level falls due to the removal of the ice (and the gravitational attraction on the ocean water).

Patterns of sea level change due to thermal expansion have also been shown to be regionally variable due to regional variations in the ocean warming. This is clearly seen in satellite altimeter measurements from TOPEX and Jason over the last 15 years when compared to ocean temperature measurements. Figure 1 shows the 15 year trends of sea level change from 1993-2007 compared to the same for thermosteric sea level change computed from ocean temperature measurements [*Willis et al*., 2004]. Clearly, much of the regional variability of sea level rise observed over the last 15 years is due to variations in ocean heat content.

The observed regional variations in sea level rise raise an important question: what will the regional patterns of sea level change be in the future? Variations in the regional rate of sea level change will have important implications for the socio-economic impact of sea level change, and in addition those patterns could be used as “fingerprints” of the various contributions to sea level change. We therefore set out to construct a crude estimate of the regional variations in sea level rise by 2100. For the thermosteric contribution to sea level change, we examined the predictions of nine different global climate models used in the most recent IPCC AR4 assessment [*Solomon et al*., 2007]. As shown in Figure 2, the differences between each of the regional model predictions is large, reflecting uncertainty in the model predictions of the regional variations in ocean heat content. Computing the ensemble mean of these model predictions (Figure 3) probably reduces the errors in the predictions, but also reduces the signal. Therefore, we chose one of the models (MIROC) to use in our predictions of regional change.

Next, we chose a value for the total value of sea level rise by 2100, and added in contributions from mountain glaciers and the ice sheets to reach this total. *Rahmstorf* [2007], as well as a number of other investigators, has suggested that sea level change by 2100 could be in excess of 1 meter. Based on this, we chose the following sea level contributions (Figure 4): 1) thermosteric – 20 cm, mountain glaciers – 25 cm, Greenland – 30 cm, and Antarctica – 25 cm, for a total of 1 meter. The ice contributions were used to scale the sea level patterns predicted by *Mitrovica et al*., [2001], assuming uniform melting across Greenland and Antarctica (highly unlikely). The sum of each of the individual contributions (Figure 4) is shown in Figure 5. While the average change is 1 meter, this varies between near zero sea level change around Greenland and the Gulf of Alaska, to nearly 1.4 meters of sea level change in the western Pacific and the Indian ocean. Sea level rise along the coast of Antarctica is roughly 0.5 meters. The coast of the U.S. would experience a sea level rise of 80 – 90 cm.

While the uncertainties associated with the map in Figure 5 are quite large, the map does demonstrate an important aspect of sea level change: the regional impact of future sea level rise will be quite variable. When combined with the effects of vertical land motion in certain regions (e.g. subsidence along the U.S. Gulf coast), the problem becomes even more complex. Therefore, studies assuming a uniform rise in sea level with no land motion will be of limited use for predicting the impacts of sea level change.

d.) Altimeter/Tide Gauge Calibration Research: Laury Miller, LSA

In addition to focusing on the problem operational altimeter/tide gauge calibration, the LSA is also interested in exploring methods for connecting non-overlapping altimetry missions, like the 4-year gap between Geosat and TOPEX. If a procedure could be developed for doing this, it would be possible to lengthen the altimetric record of global sea level rise by nearly 40%. A University of Maryland undergraduate student, Caroline Harbitz, was hired through CICS to work with the LSA on this problem. Caroline worked full-time last summer (2007) and over the winter semester break (January, 08), preparing tide gauge data sets used in analysis of the Geosat/TOPEX gap. A paper describing some preliminary results was presented at the Jason-1/OSTM Science Working Team meeting in Hobart, Tasmania, and also at the AMS Satellite

Meterology & Oceanography Conference, in Amsterdam. The plan is to finish this project this Summer (2008), with a paper submitted for publication. (*In part, as result of her work with the LSA, Caroline is planning on applying to WHOI, URI/GSO, and LDO graduate programs next Fall).*

e.) Altimeter/Tide Gauge Calibration Web Site: Nancy Soreide, PMEL

The purpose of this project is to provide on a routine monthly basis a consistent set of tide gauge datasets (developed under other funding) for the calibration of current and historical satellite altimeter datasets. The work is being done at PMEL, under the direction of Nancy Soreide, with science guidance from Dr. Gary Mitchum, University of South Florida. A preliminary version of the public Tide Gauge Altimeter website has been installed in the Seattle Web Farm environment. The URL is http://www.altcal.noaa.gov/. The Overview, Methods and Links sections of the website provide background information that describes and explains the data on the website.

On the Products section of the website, at http://www.altcal.noaa.gov/products.html, the user can: 1. See Tide Gauge station locations on a map; 2. Click links to view single time series plot; 3. Check the box to select plot and click "Display Plots" to display multiple plots; 4. Click on to download netCDF file; 5. On the web page presenting the results, (called the "result" page), the user can also "enlarge plot" and "download data".

PHP scripts have been developed that dynamically create the product results graphics and data download pages and perform these functions. The next step is an automated system to retrieve data/plot files from USF's ftp server to PMEL's web server on a routine and regular basis. Once the files have been properly prepared on the USF server and the automated retrieval procedure has been activated, the PHP scripts will be used to present the data/plots to the user through a web interface.

Publications and Reports:

Miller, L., and B.C. Douglas, "Gyre-scale Atmospheric Pressure Variations and their Relationship to 19th and 20th Century Sea Level Rise", *Geophys. Res. Lett.,* **34**, L16602, doi:10.1029/2007GL030862.

Ohring, G., J. Tansock, W. Emery, J. Butler, L, Flynn, F. Weng, K. St. Germain, B. Wielicki, C. Cao, M. Goldberg, J. Xiong, G. Fraser, D. Kunkee, D. Winker, **L. Miller**, S. Ungar, D. Tobin, J. G. Anderson, D. Pollock, S. Shipley, A. Thurgood, G. Kopp, P. Ardanuy, and T. Stone (2007), ASIC3 Report in EOS, "Achieving Satellite Instrument Calibration for Climate Change," Eos Trans. AGU, 88(11), 136.

Miller, L., R. Scharroo, J. Kuhn, C. Harbitz, "Extending the TOPEX/Jason global mean sea level time series with GEOSAT observations", Jason-1/OST Science Working Team Meeting, Hobart, Tasmania, 2007.

Leuliette, E. W., (2008) Interpreting the sea level rise record from satellite altimetry, Ocean Sciences Meeting, Orlando, Florida, 2-7 March 2008.

Leuliette, E. W. and W. H. F. Smith (2008), Interpreting the ocean mass contribution to sea level change, Eos Trans. AGU, 89(23), Jt. Assem. Suppl., Abstract G31B-07.

Nerem, S., D. P. Chambers, J. Famiglietti, and **E. Leuliette**, (2007) Hydrologic contributions to global mean sea level, IUGG XXIV General Assembly, Perugia, Italy, July 2-13, 2007.

Nerem, R. S., D. Chambers, G. Mitchum, and **E. Leuliette** (2007), Building a Climate Record of Sea Level Change, Eos Trans. AGU, 88(52), Fall Meet. Suppl., Abstract G33B-1244.

Appendix A. Predictions of Regional Sea Level Change Patterns by 2100: Figures & References

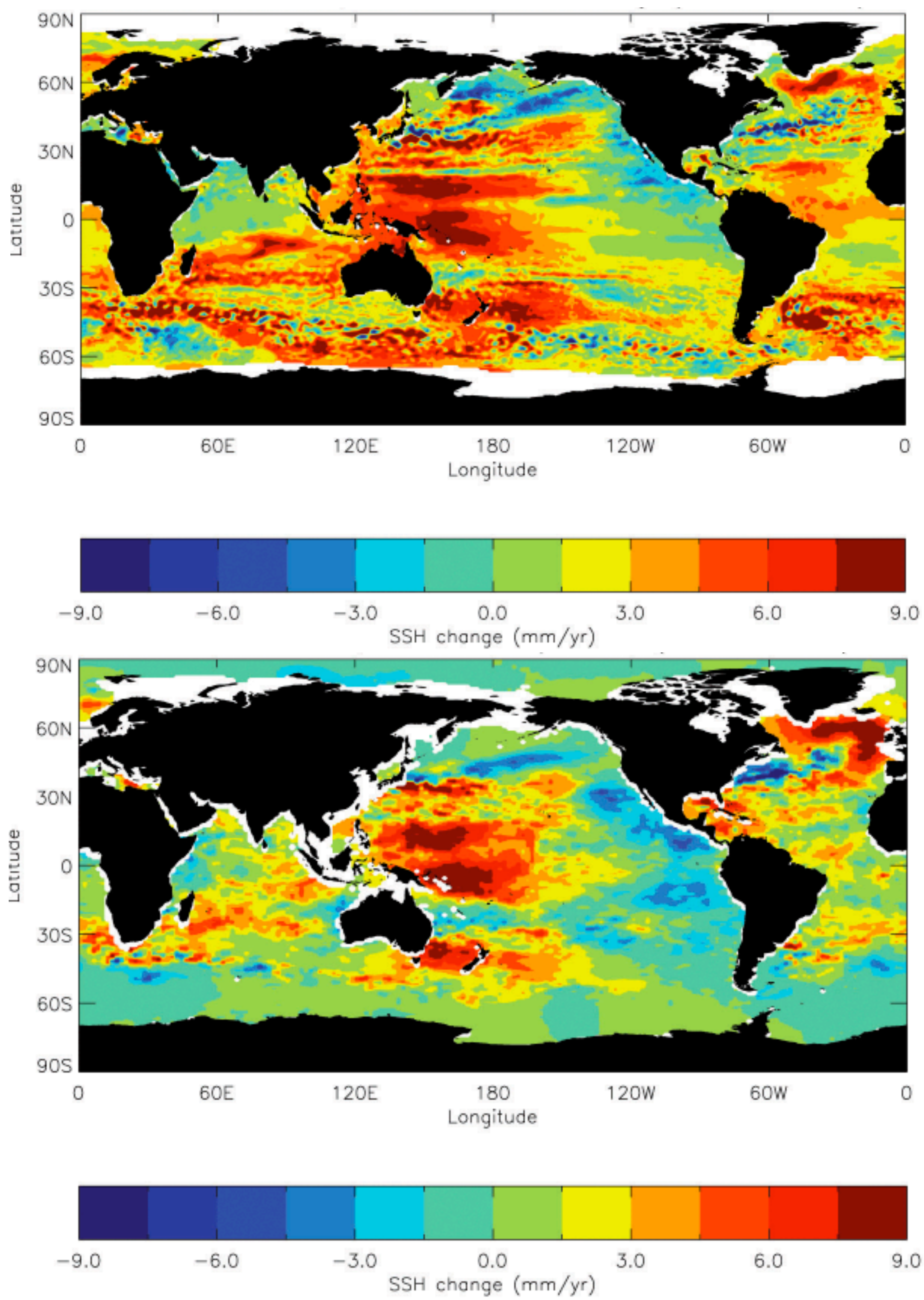

Figure 1. Regional variations in the trend in total sea level change over 1993-2007 as observed by TOPEX and Jason (top) and the trend in thermosteric sea level change over the same time period as observed by ocean temperature measurements (bottom) [*Nerem et al.*, 2007].

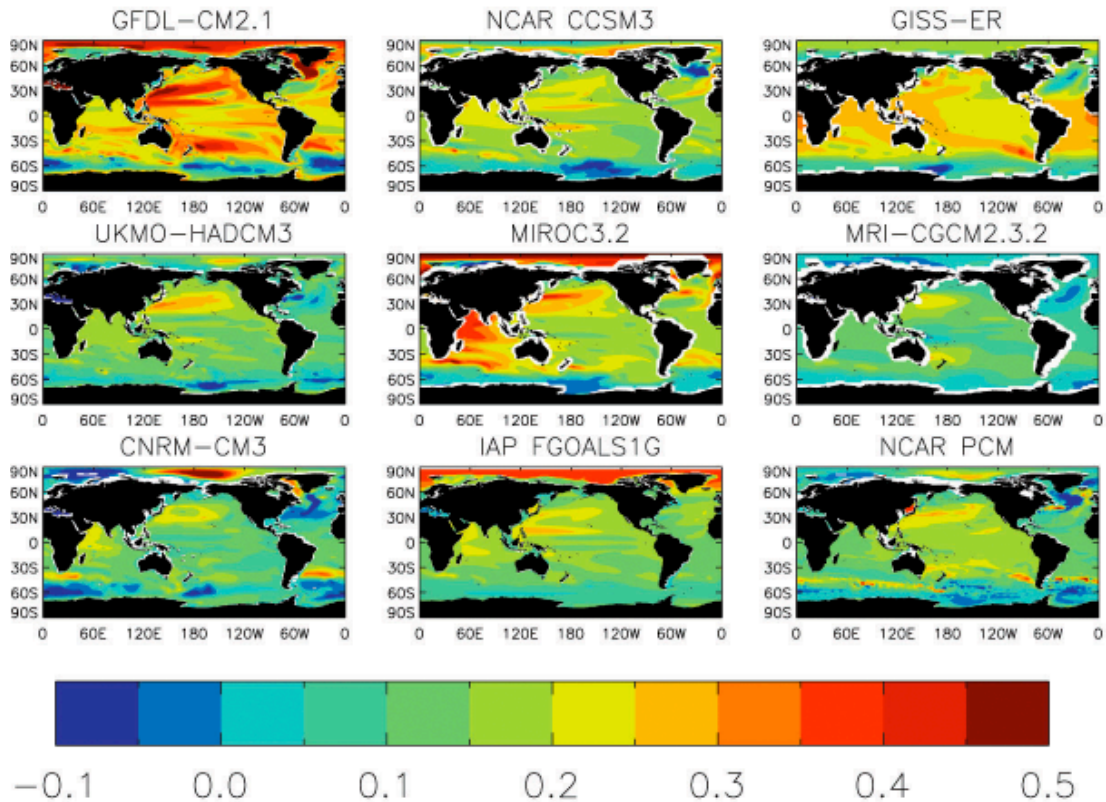

Figure 2. Predictions of regional thermosteric sea level change predicted by 9 different models from the IPCC AR4 assessment.

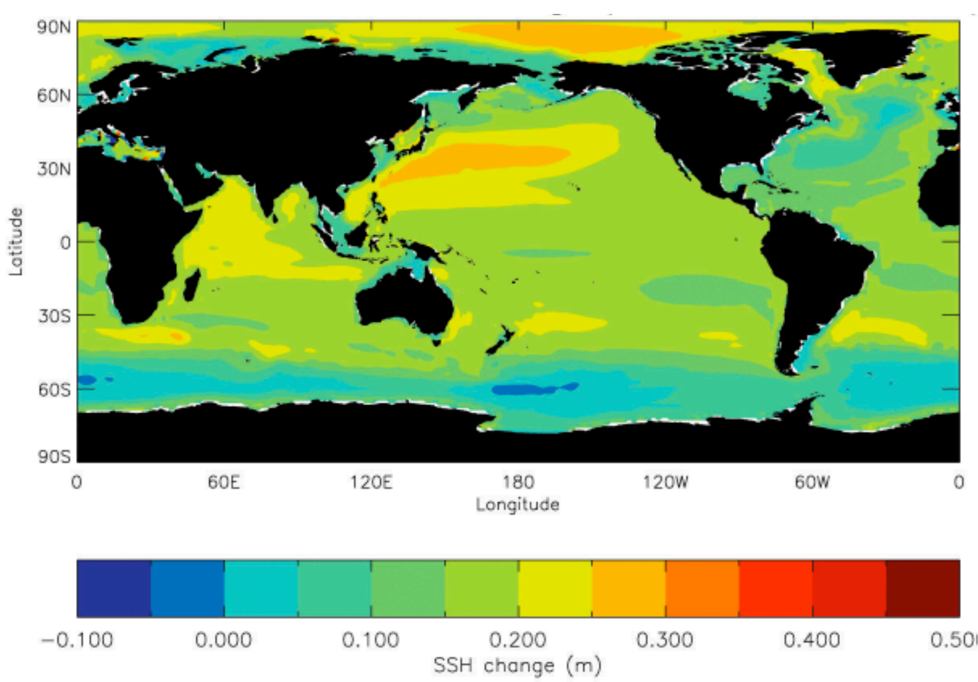

Figure 3. Ensemble mean of the predictions of thermosteric sea level change shown in Figure 2.

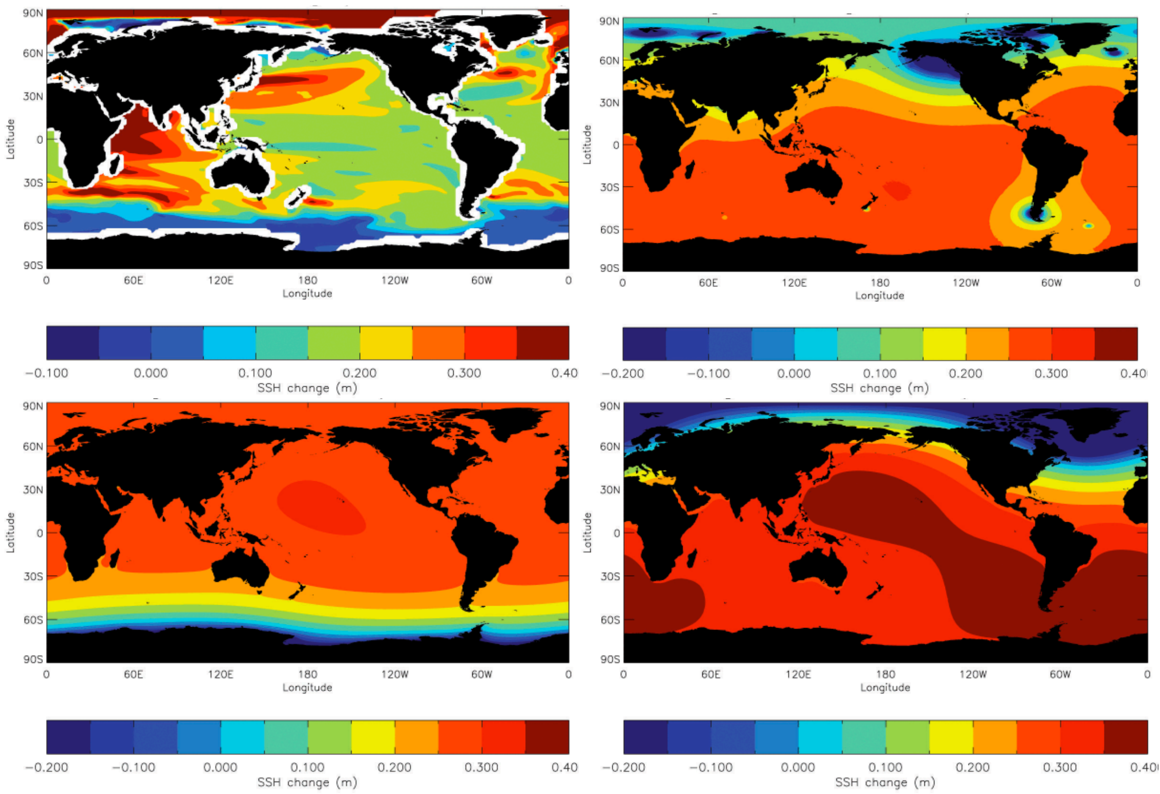

Figure 4. Patterns of sea level change expected from thermosteric change (top left), melting of mountain glaciers (top right), melting of Antarctic ice (bottom left), and melting of Greenland ice (bottom right).

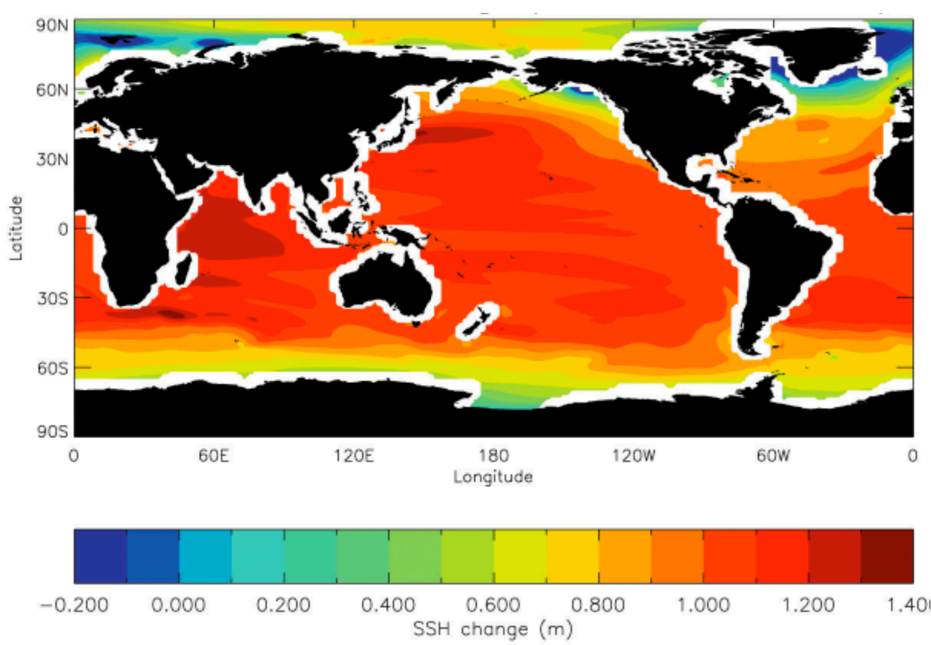

Figure 5. A prediction of regional patterns of sea level change by 2100 assuming the following globally averaged contributions: steric (20 cm) from the MIROC model, mountain glaciers (25 cm), Greenland (30 cm), and Antarctica (25 cm), for 1 m of global average sea level change by 2100.

References:

Mitrovica, J. X., et al. (2001), Recent mass balance of polar ice sheets inferred from patterns of global sea level change, Nature, 409, 1026-1029.

Nerem, R. S., S. Doris, J. K. Willis, D. P. Chambers, and G. T. Mitchum, Satellite and In Situ Observations of Regional Sea Level Change: What can they tell us about future changes?, *Eos Trans. AGU*, 88(52), Fall Meeting Suppl., Abstract G44A-01, 2007

Rahmstorf, S. (2007), A Semi-Empirical Approach to Projecting Future Sea-Level Rise, Science, 315, 368-370.

Solomon, S., et al. (Eds.) (2007), Climate Change 2007: The Physical Science Basis, Cambridge University Press.

Willis, J. K., et al. (2004), Interannual variability in upper ocean heat content, temperature, and thermosteric expansion on global scales, J. Geophys. Res., 109, doi:10.1029/2003JC002260

Appendix B. Altimeter/Tide Gauge Calibration Web Site: Example pages.